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Energy Potential from Construction and Demolition Wood Wastes

JACA Corp, Fort Washington, Pa

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ENERGY POTENTIAL FROM CONSTRUCTION AND DEMOLITION WOOD WASTES

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The National Volume of Wood Wastes from Construction is estimated at 2.6 million tons and demolition Wastes at 19.3 million tons annually. If the energy potential could be recovered, it would have an annual heating value of 3.75 x 10^14 BTU. This heating value is equal to 16 percent of the forest and industrial waste stream or 2 percent of total cost consumption annually.

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Estimating Demolition Wastes
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Volume of Construction Wastes
Wood Wastes Construction
Wood Wastes Demolition
Energy Potential Construction Wastes
Energy Potential Demolition Wastes
Density Demolition Wastes
Density Construction Wastes

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PREFACE

Energy shortages and the need to conserve natural resources have led the United States to examine its waste streams as sources of potential supplies of energy and reconstituted products. While solid waste energy potentials in the private sector have been examined in some detail, construction and demolition wastes have not heretofore received comparable study attention. Therefore, the first step in analyzing a reuse program is the development of the size and nature of the particular waste stream.

The objective of this report was to determine the nationwide volume of construction and demolition wastes, and, in particular, the combustible fraction of wastes from these activities. Ancillary outputs of the study are annual generation rates by location, information on time variation in waste flows, and the distribution of wood fractions.

Appreciation is expressed to the National Association of Demolition Contractors, their president Mr. Ron Dobell, Mr. William Baker, Executive Secretary and members of the NADC Energy Recycling Committee for providing valuable assistance in scheduling fieldwork and for the administration of a response card program regarding volumes of waste generated per demolished building. We are also grateful to Mr. Mike Sabia of Domino Salvage who assisted us in the training phase of the program, and Mr. William Geppert of Geppert Brothers who helped in some of the original planning aspects of the work.

The twelve month study was conducted by JACA Corp. of Fort Washington, PA under contract number 68-01-3560 with the Office of Solid Waste Management Programs of the Environmental Protection Agency in 1976. The EPA project manager was John W. Thompson. The principal investigator was James A. Cummins. Researchers were H. Baist, G. Gindlesperger, G. Lesher, E. Mathis, and W. Ott.

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SUMMARY

Based on a 1976 survey of 10 cities, the annual volume of wood wastes from construction and demolition wastes is 2.57 million tons. Projected to a national basis by statistical means, the annual tonnage of wood waste from demolition and construction waste is estimated at 21.9 million tons annually. Demolition wood wastes accounts for 19.3 million tons and construction wood wastes 2.6 million tons of this total.

If the energy potential of these wood fractions could be recovered it would have an approximate heating value of 3.75×10^{14} BTUs. This heating value is equal to about 16 percent of the forest and industrial waste stream or 2 percent of the total coal supply.

Several significant aspects about the waste stream from the demolition and construction industry resulted from the study:

(1) The average density of construction and demolition debris at disposal sites is 25 pounds per cubic foot.

(2) The average load of demolition debris contains about 39 percent wood and construction wastes 46 percent wood. However, these averages are deceiving because loads tend to run either 10 percent wood or 80 percent wood content.

(3) The average duration of a demolition job is 3.87 days for residential, 14.7 for industrial, and 9.56 for commercial buildings.

(4) The average volume of a demolition job is 450 cubic yards for residential, 3,856 for industrial and 3,022 for commercial.

(5) The percentage of wood by weight with respect to other construction materials has been steadily decreasing over the last 25 years to a low of 9.8 percent in 1971. Estimates of wood waste in the construction industry averaged 7.4 percent of deliveries.

(6) High risk and entrance costs due to separation problems, sporadic supply and undeveloped markets stymie the reuse of demolition and construction wood wastes. However, there are two small firms in California marketing pre-screened construction and demolition wood waste to the pulp industry.

RECOMMENDATIONS

(1) The energy and/or product potential of demolition and construction wood waste is sufficiently large to merit further investigation on two critical points - separation techniques (and costs) and market potentials.

(2) Risk and rate-of-return characteristics however are such that it is doubtful that private enterprise will undertake a program to reuse such wastes at present energy costs. It is recommended that the federal government consider the feasibility of lessening the risk and improving the rate-of-return expectations so that private parties will enter this market.

(3) The seldom used concept of separate dump sites for demolition and construction waste should be examined for technical and economic viability.

BACKGROUND

Wood waste from primary and secondary manufacturing and from logging operations have been estimated at 16 million tons and 118 million tons respectively.[3] This estimated waste is more than two times current U. S. total pulpwood fiber needs. Based on this study, the amount of wood waste available from demolition and construction waste are of the same order of magnitude. The total waste from wood processing plants and logging forest waste is 134 million tons versus 21.9 million tons for demolition and construction waste.

Some of the process and forest wastes have been put to energy saving uses. Applications have included direct use of these wastes as fuels or as fuel supplements. Indirect energy savings uses have been for mulch, medium density particle board, cattle bedding[4] and grading for recreational areas[5]. An industry has grown up around this reuse of wood wastes. There are more than twenty manufacturers[6] of equipment for the handling and/or disposal of trees and wood wastes. Of these, however, seven are manufacturers of air current destructors, whose primary purpose is to reduce the volume of waste by burning without recovering the heat.

Plants that use large quantities of wood in fabrication of finished products often use the wood as a fuel source or supplement to produce heat or steam for local operations. There are a wide variety of furnaces especially designed for burning wastewood fuel. The variety of furnace techniques is quite broad, and includes fluidized beds, inclined grates, dutch oven, spreader-stoker, fuel cell, hogged fuel and sawdust burners, sander-dust burners, etc.

The greatest use of wood for fuel or a fuel supplement takes place at these wood fabricating plants, where a constant supply of wastewood is available and an on-site fuel need exists. The situation here is analogous to "home scrap" where there is a ready raw material supply and a local need.

While the woodwaste from demolition and construction waste estimated in this study is of the same order of magnitude as that from municipalities and processing plants, there are certain peculiarities in its generation and composition which aggravate problems associated with its productive reuse or direct use as a fuel or fuel supplement.

Demolition waste is generated when buildings are demolished because of fire, unsafe conditions, or to make way for other buildings or alternate land use. The business is served by more than two thousand demolition contractors, most of them small operators. Demolition jobs are short lived. This study showed average job spans of 3.27 for residential, 9.56 days for commercial buildings, and 14.7 days for industrial buildings. Choice of a dump site is governed by optimizing the combination of dumping fees and hauling expenses. Hauling is customarily done by the demolition contractor often using special trucks to facilitate loading and unloading bulky materials.

The generation of construction waste is quite different. It is generated from cutting material to size and from breakage and wear out of materials such as concrete forms and scaffolding in the construction of buildings. A construction job is a much longer term project than a demolition job, ranging from a month to more than a year. General contractors seldom haul their own waste. Usually they contract with private haulers who utilize bins which are left at the site and periodically removed. Often each sub-contractor is responsible for removing his waste, and this gives rise to a multiplicity of storage and hauling arrangements.

The amount and source of wood waste generated varies considerably during the several phases of constructing the foundations, shell and interior.

The common thread in both types of waste is that they are highly heterogeneous both as to composition and size. Neither contain putrescibles, but both can contain brick, stone, metal, glass, wood, impregnated paper, mortar, cinderblock, and other detritus. Size of the waste can vary from small wood fragments to large chunks of reinforced concrete, timber, sheets of metal roofing, etc. The waste is highly varied insofar as size, weight, density, hardness, and other physical attributes.

If this waste is to be seriously viewed as a material resource or a fuel, characteristics of its generation and present disposal must be better understood in terms of amounts, predictability of supply, use technology and use economics. This study focused on the first two aspects of the problem - amounts and predictability of supply.

NATIONAL AND AREA ESTIMATES

Construction and demolition activities were studied in ten cities; Philadelphia, Los Angeles, Chicago, Houston, Detroit, Miami, St. Louis, Atlanta, Pittsburgh, and Minneapolis with the emphasis on determining the combustible fractions present in these wastes at area landfill sites. Demolition and construction rates for each city as well as heating values for various wastes and fuels were analysed to determine the potential energy represented by these combustible fractions.

Tonnages of construction and demolition wastes and the nominal energy potential vary considerably by city and region of the nation. Of the ten cities studied, Atlanta exhibited the lowest annual potential, .72 x 10^{12} BTUs, while Los Angeles, Chicago and Detroit were clustered at the high end; Houston, Miami, Minneapolis, Pittsburgh, and Atlanta at the low end; and Philadelphia and St. Louis near mid-range on Table 1.

Table 1

ANNUAL TONS AND BTU POTENTIAL OF WOOD WASTE
FROM CONSTRUCTION AND DEMOLITION WASTES
OF 10 CITIES IN 1976

City	Thousand Tons	BTU Potential
Philadelphia	190	3.3×10^{12}
Los Angeles	670	11.0×10^{12}
Chicago	400	6.0×10^{12}
Houston	110	1.9×10^{12}
Detroit	490	8.5×10^{12}
Miami	67	1.1×10^{12}
St. Louis	250	4.0×10^{12}
Atlanta	42	$.72 \times 10^{12}$
Pittsburgh	100	1.8×10^{12}
Minneapolis	67	1.2×10^{12}
Average	237	4.0×10^{12}

Demolition rates vary from city to city, as can be seen on Figure 1. Source cities also display large variations from year to year, viz. Detroit, St. Louis, Cleveland, Dallas, and Kansas City. Construction and demolition activity in Philadelphia and Portland respectively are shown on Figures 2 & 3 as a function of month. Both indicate, as one would expect, lower demolition activity than construction. Both graphs show that construction and demolition activity can have swings for a year of 100 percent. This is not apparent by a cursory comparison, since the level of construction is so much greater than the level of demolition activity. Several trends in building construction rates and construction materials are discernable:

- Construction rates of non-residential units from 1957 through 1974 were less volatile than residential unit rates. Both rates were , in 1974, about equal to those of 1957 (Figure 4)[2].

- Construction of residential units is expected to move to a higher level through 1981 (Table 2).

- Building construction is on the increase thus wood consumption in the building and construction industry continues to increase (Figure 5). Shipments of wood to U. S. building and construction have increased about 30% from 1951 to 1971. However, wood used per building as a percent by weight of other materials has experienced a persistent decline from 13.5% in 1951 to 9.8% in 1971 (Figure 6).

- Recent technical trends in the building industry have reduced the amount of wood per structure. For example, modern scaffolding uses more pipes and clamps than the older all wood scaffolds. Also the wooden forms used in concrete work are being replaced by plastic or metal forms. Moreover, there is an increasing amount of metal, especially aluminum, being used in metal frames, door jambs, and siding in commercial and industrial buildings.

At the disposal sites, the average percent combustibles in demolition waste was 80% and the average in construction waste 48%. The reason these averages tended toward the midrange is due to the "U" type distribution of the observed waste loads, where waste compositions were clustered at the high and low ends of a distribution curve. A Frequency plot of the distribution based on 1001 field observations is shown in Figure 7.

The nominal heating value of various fuel sources are shown in Table 3. The heating values, of course, cover a range but those nominal values shown were chosen for comparison purposes. The heating value of wood is about midway between fuel values from commercial, residential and industrial wastes, and that of coal. Using this value, and the 21.9 million tons of combustible demolition and construction waste this study estimated that the total energy potential which would be generated annually would be approximately 3.75×10^{14} BTUs.

Figure 1

RECENT HOUSING UNIT DEMOLITION RATES

IN MAJOR U.S. CITIES

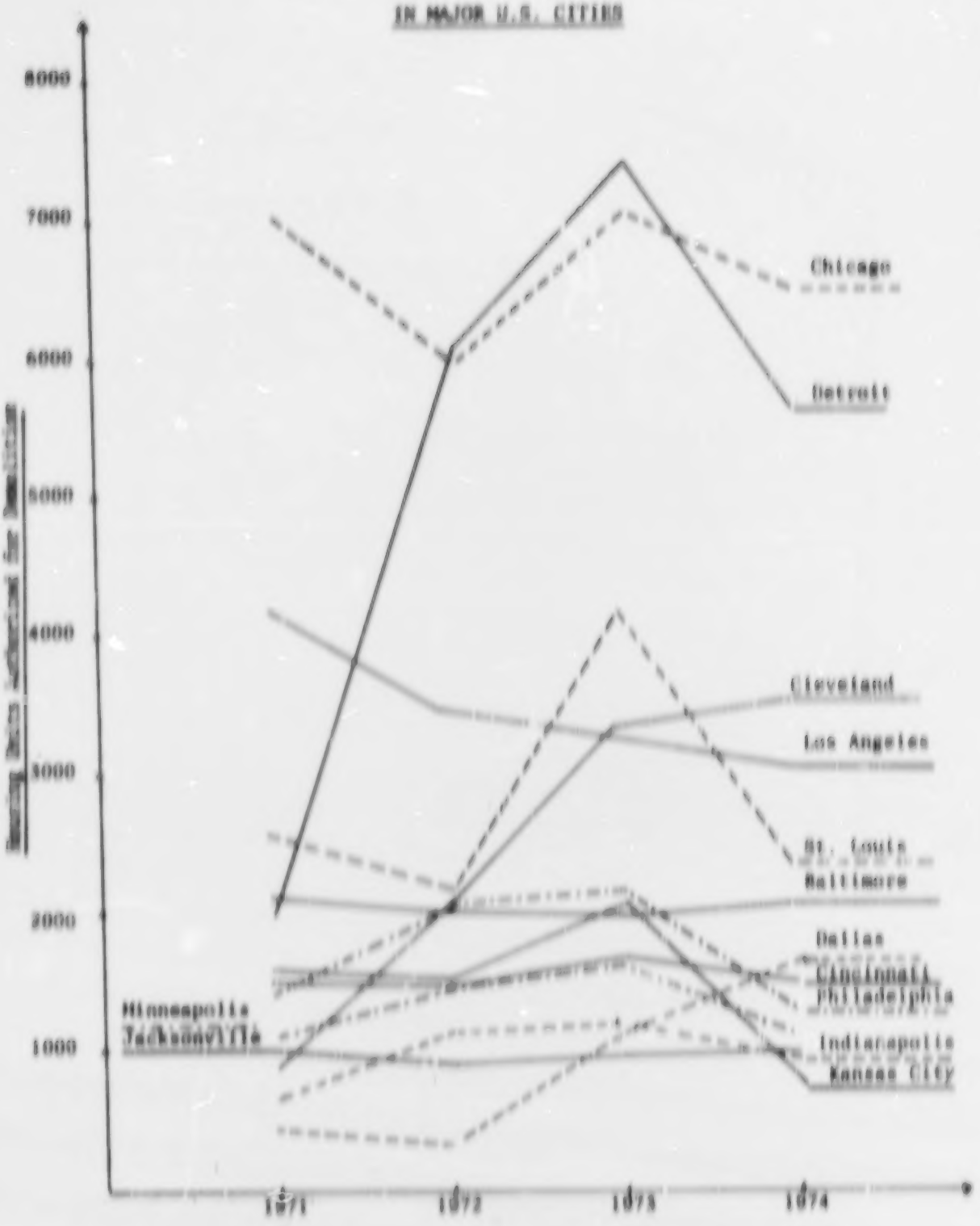


Figure 1

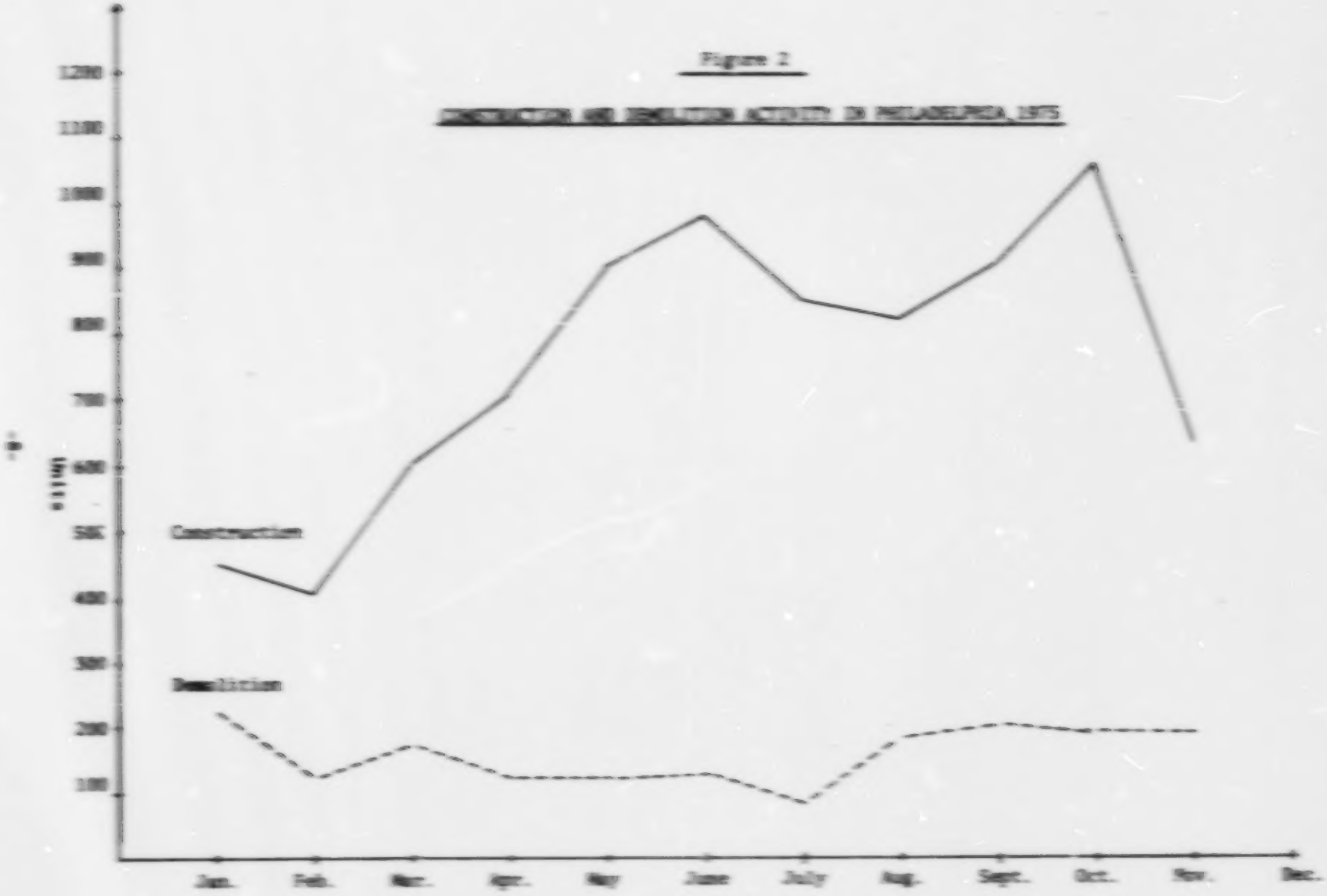
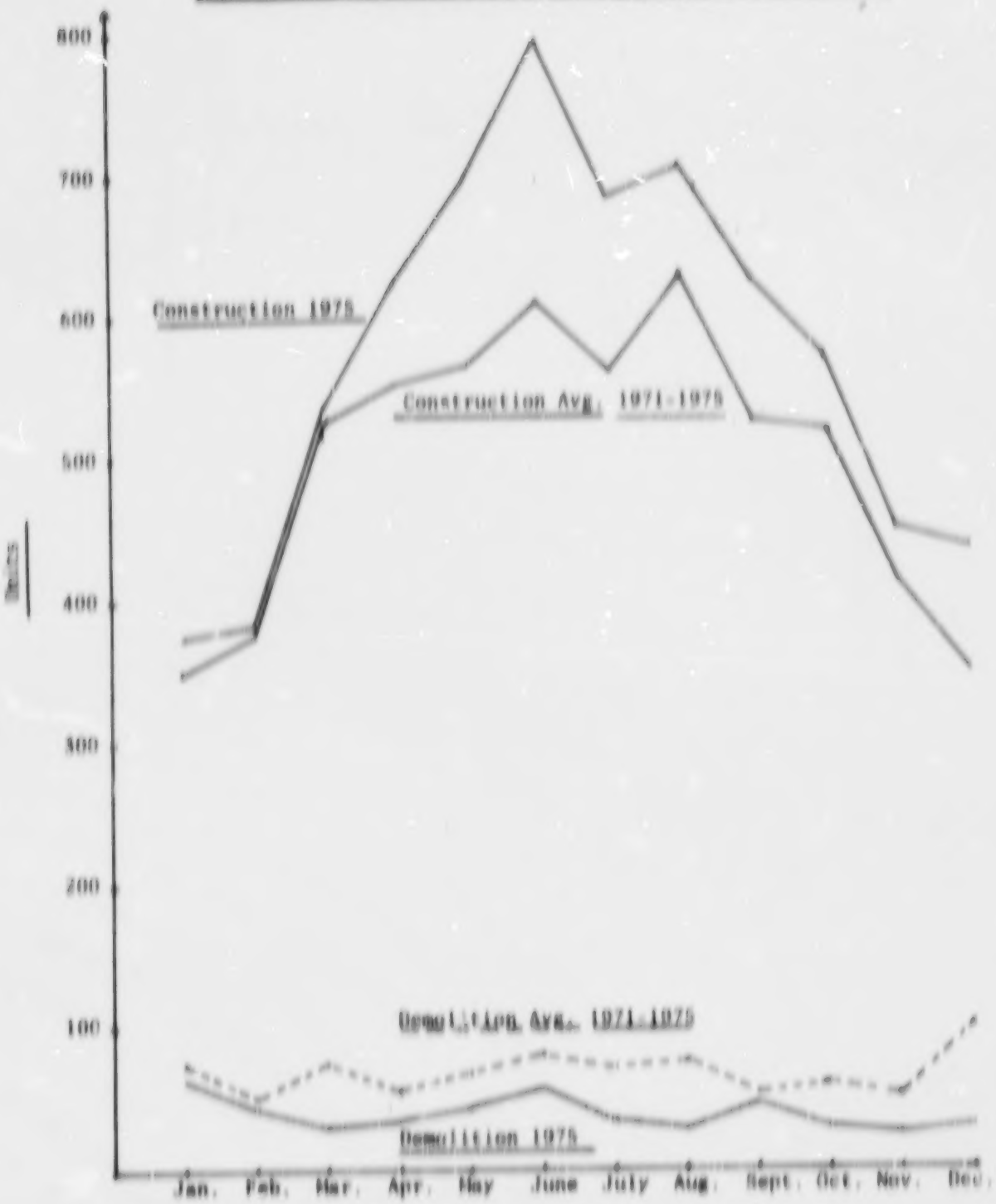
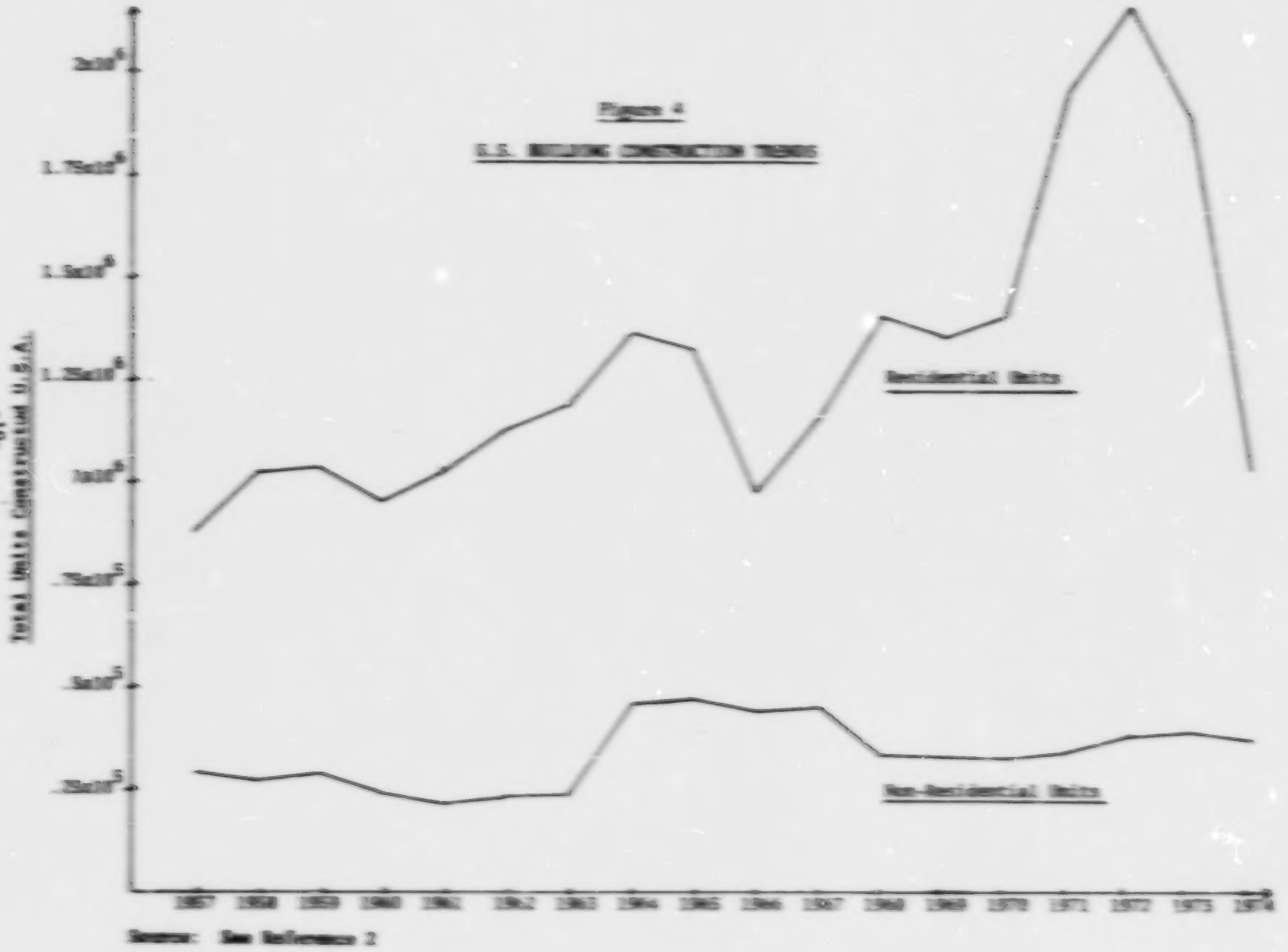

Construction
Demolition
Jan.
Feb.
Mar.
Apr.
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.

Figure 3

CONSTRUCTION AND DEMOLITION ACTIVITY IN PORTLAND, 1971-1975





Source: See Reference 2

Table 3

PROJECTED CONSTRUCTION RATES FOR

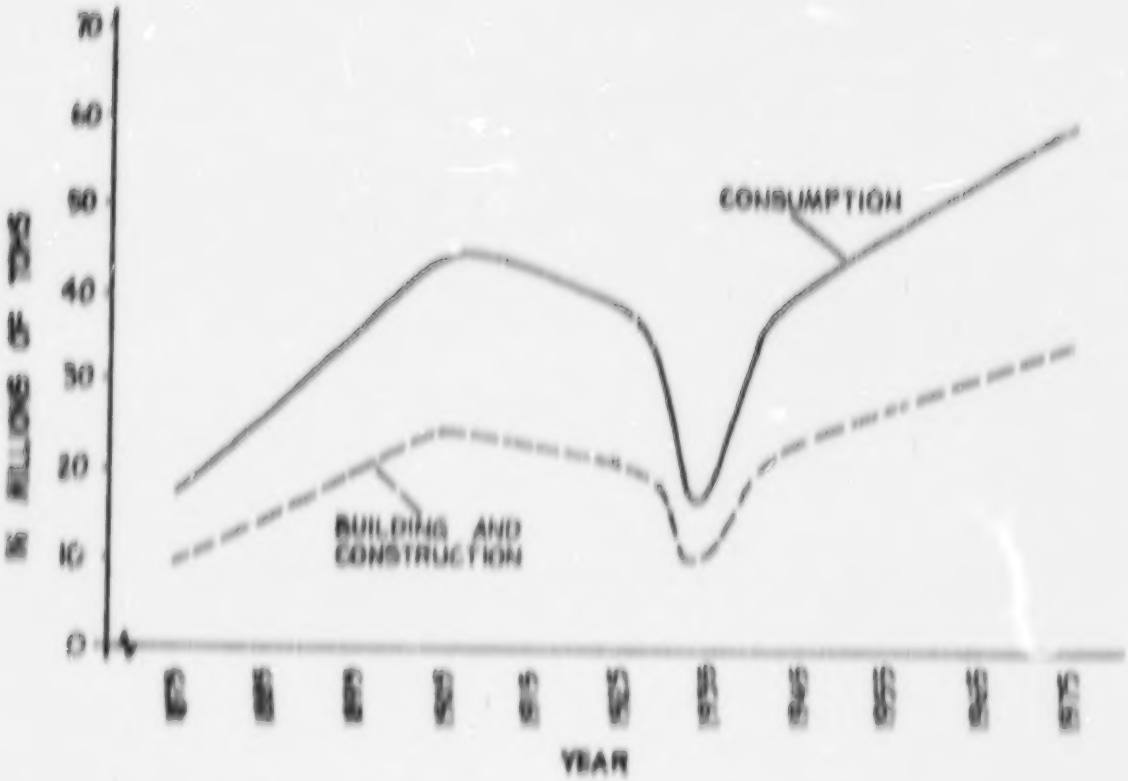
RESIDENTIAL UNITS

	Projected Residential Units
1976	1,512,000
1977	1,770,100
1978	1,444,000
1979	1,650,000
1980	1,790,000
1981	1,870,000

Source: National Association of Homebuilders

Figure 5

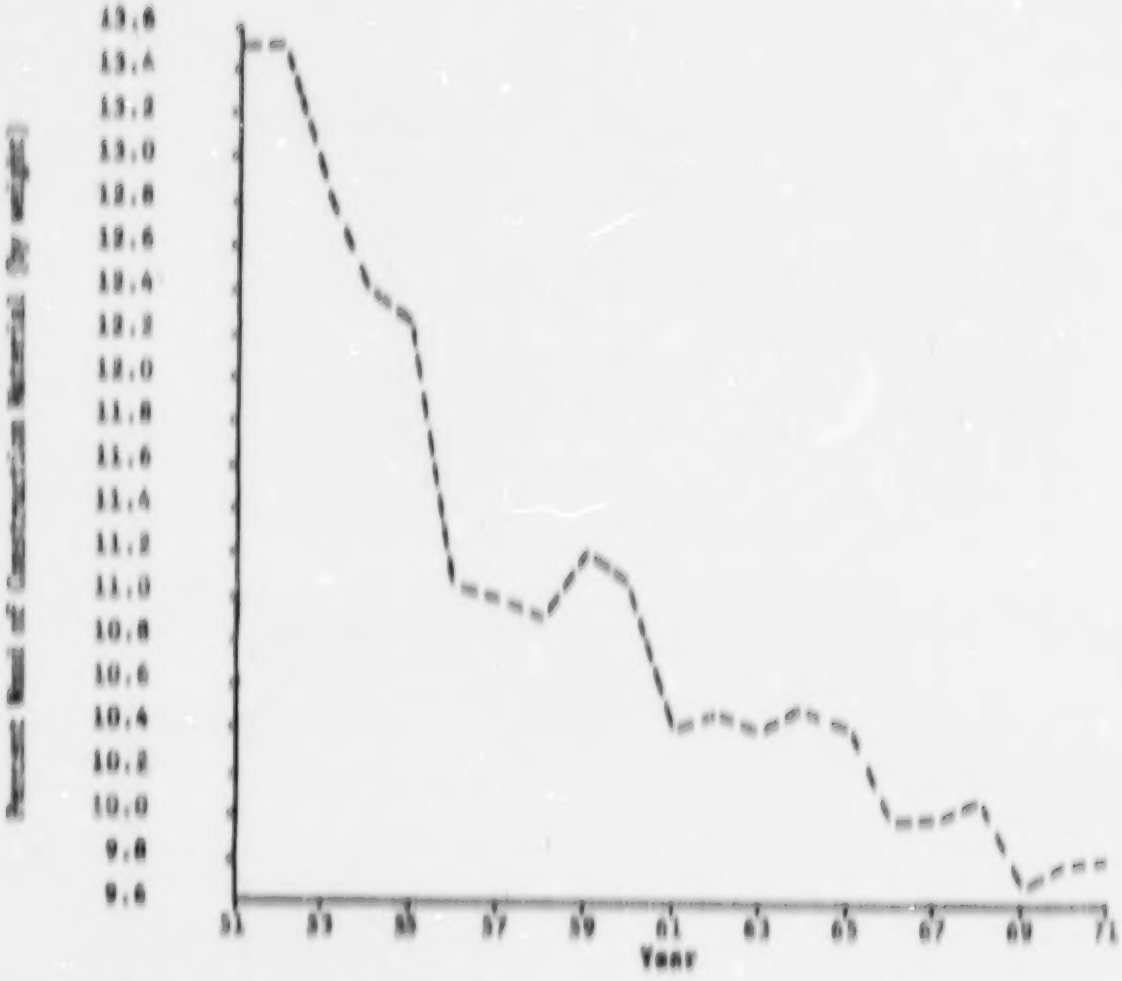
U.S. WOOD CONSUMPTION AND
SHIPMENTS TO BUILDING AND CONSTRUCTION



Source: See Reference 2

Figure 6

PERCENT WOOD IN CONSTRUCTION MATERIAL (BY WEIGHT), 1951-71

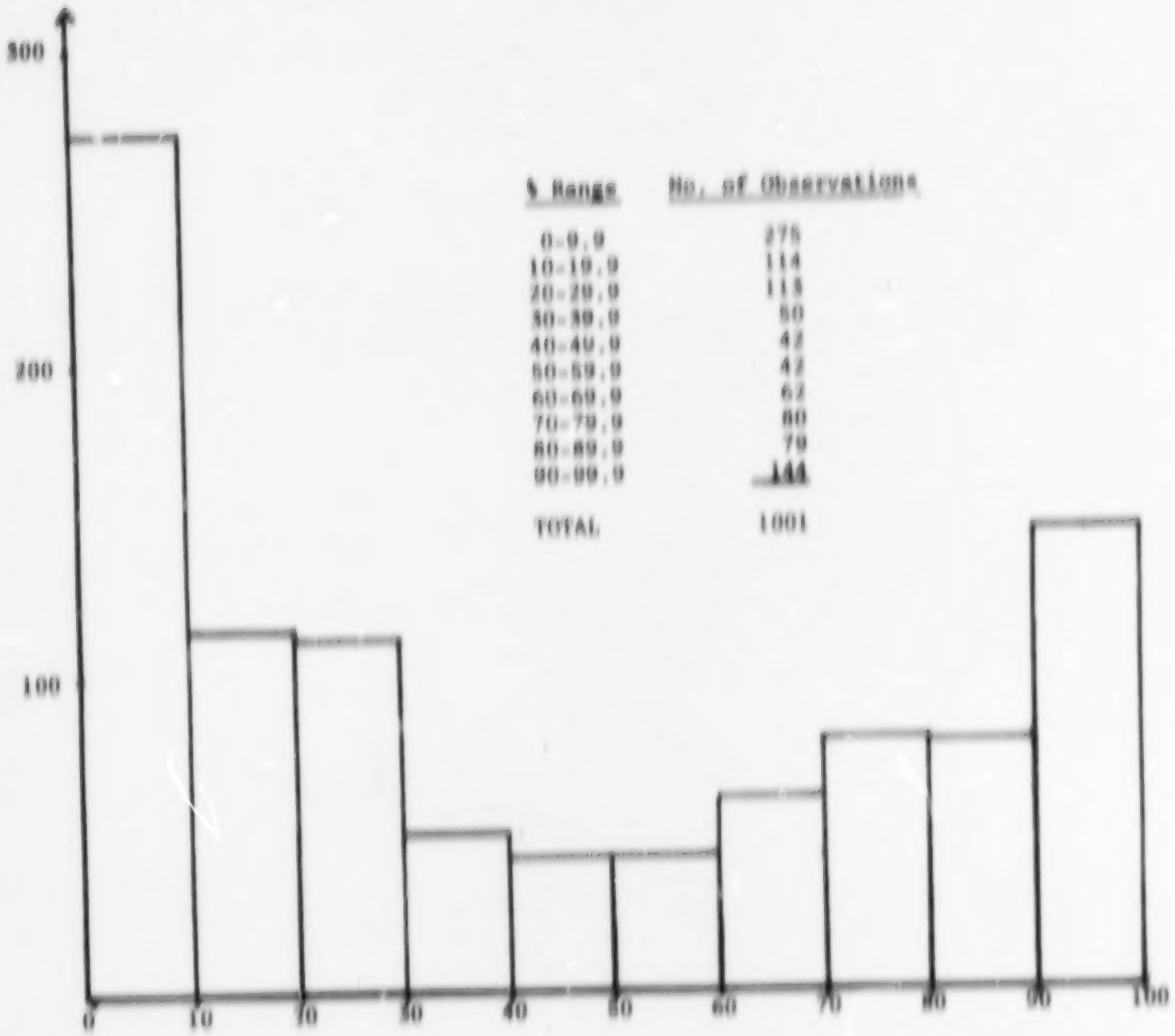


Source: See Reference 9

Figure 7

FREQUENCY DISTRIBUTION OF

PERCENTAGE COMBUSTIBLE DATA



% Range	No. of Observations
0-9.9	275
10-19.9	114
20-29.9	115
30-39.9	50
40-49.9	42
50-59.9	42
60-69.9	62
70-79.9	80
80-89.9	79
90-99.9	144
TOTAL	1001

Estimated % Combustible

Table 3

NOMINAL HEATING VALUE OF VARIOUS WASTES AND FUELS

Type of Waste or Fuel	Heating Value (1000's BTU/lb)
Commercial Wastes	4 *
Residential Wastes	5 *
Industrial Wastes	6 *
Wood Wastes	8.6*
Anthracite Coal	13.6**
Bituminous Coal	14.1**
Natural Gas	1049.6 BTU/Ft^3 **
No. 2 Fuel Oil	19.9**

* Source: See Reference 7
** Source: See Reference 8

Table 4

COMPARISON OF ANNUAL BTU POTENTIAL

	BTU x 10^{14}
Pennsylvania Anthracite	1.9 **
Bituminous	162.5 **
Total BTUs from Coal	164.4 **
Demolition & Construction Waste	5.75 *
Forest and Primary and Secondary Wood Industry Waste	25. ***
% Fuel Value in Demolition & Construction Compared to Forest and Wood Industry Waste	16% *
% Fuel Value in Demolition and Construction as Compared to Coal	2% *

* Source: JACA primary data and calculations
** Source: See Reference 8
*** Source: See Reference 3

ECONOMICS OF WOOD RECOVERY

The supply-demand relationship for waste wood either as a fuel or as a product is quite elastic because of the ready opportunity for substitutions of other supplies that can satisfy the same demand. For example, as a fuel, waste wood would be in price competition with gas, oil, and coal. Virgin material would compete in paper puiping and construction.

There are three technical factors that affect the demand for waste wood. These are (1) availability, (2) ability to separate and (3) quality of recoverable wood fiber.

A predictable supply of wastewood of sufficient quantity to serve a reuse facility for either demolition or construction waste is an important problem. It is difficult for any potential reuse operational site to predict the level of demolition and construction activity over a time period commensurate with a sizeable capital expenditure having an attractive return-on-investment. The return-on-investment analysis has two ingredients, the expected rate of return and the duration of that return. A break even analysis is only meaningful in the context that the return will continue for some appropriate period after the breakeven point has been reached. It is during this period, subsequent to the breakeven point, that the major returns will be realized.

Demolition and construction activity vary considerably over time, and geographic locations as indicated by the data on demolition activity and the information on new construction in Figures 1, 2, 3, and 4. Furthermore the study indicated that it is difficult to anticipate construction and demolition activity several years in advance.

Inability to accurately predict the supply of demolition and construction waste can be translated into the necessity of having large storage facilities to accommodate supply surges and to provide buffer storage at times of low levels of supply.

The second problem with supply of demolition and construction waste is that an added step with respect to wood waste recovery presently being practiced must be taken. The waste is a mixture of building materials including wood, impregnated paper, bricks, concrete, metals, glass, plastics, stone and clay products. This waste must first be separated into its principal components, i.e. wood combustibles, stone, brick, clay or concrete, and metals. Ancillary to this separation process is the necessity of having the ability to dispose of the waste components, other than wood, on site. This study indicated that for construction waste an average of 48% was wood and for demolition waste 50%. Thus the separation process will result in disposal of large quantities of non wood waste.

The mixture of woods, degree of weathering, moisture content, and the tendency of the wood to retain bits of concrete, soil, brick, etc. poses a quality

control problem. If the wood is to be used as fuel then the principal restrictions are on size and moisture content. High moisture content wood might require pre-drying. Chips used as pulp in paper operations tend to have more strict specifications as to appearance and foreign material. The relatively new, and in most cases experimental use of wood chips in such construction material as particle board, has not yet generated quality standards. Currently, some research effort is being directed toward quality standards.

The above three points concerning available supply, need to separate, and quality control are a strong inhibiting force in the use of demolition and construction wood wastes. The other side of the problem involves market demand for recovered wood.

To be economically viable,any conversion to a new product or fuel use of the wood fraction found in demolition and construction,must have long range markets. At present, there is practically no use made of such wood waste because of the technical, economic and institutional problems associated with the three major potential uses of such waste.

Wood Fraction as a Fuel or Fuel Supplement

Demolition disposal operations do not require fuel. Potential users in the economic area of the disposal site must have special equipment for utilising the wood fraction such as:

- Conveyors are necessary for feeding wood into the furnace
- A furnace for wood combustion is needed
- A handling system for ash by-product is necessary
- Air pollution control devices are needed.

Wood Fraction as Pulp Fibers

- Economics in transportation call for close proximity to user.
- Dirt, differences in color or texture cannot be tolerated in some paper plants.
- Asphaltic substances may be deleterious to paper production.

Wood Fraction as a Building Material Substitute

- No waste wood product is now used.
- Building code requirements must be met when product is available.
- The reluctance to accept new products on the part of building trades, unions, and other construction industry personnel must be overcome.

In most instances the market FOB user site for wood from demolition and construction waste processed at a dump or other central point would have to recover these costs:

- Separation from non-wood waste
- Disposal of non-wood waste
- Reduction in size and screening for use
- Pre-drying for some selected uses
- Delivery to site
- Transportation to user
- Profits for operator.

An offset to these costs is the fee for dumping the material, which may run from $17 to a high of $120 for a 50 cubic yard load. Also as disposal sites become more scarce, there will be an increase in dumping fees. The break even equation becomes:

Disposal fee + wood product recovery returns = processing costs

on an annualised basis:

$$\frac{\text{Disposal fees + Product sales}}{\text{Year}} = \text{Annualised Cost (depreciation, O \& M, taxes \& insurance)}$$

PILOT PLANT OPERATION

Two operations were identified and visited during the course of the study that partially approached an operation for recovery of demolition and construction waste. Both operations had contracts with one or more paper manufacturers to deliver wood fibers for pulping operations.

The first system located in San Francisco used a total dry operation to produce the fibers from wood debris from building, industrial and food processing industries.

The raw waste, usually picked clean of plastic-sheet and bags which could clog the screens, is first broken by running over it with a crawler-tractor. The broken waste is then pushed by the tractor into a recessed part of the steel faced reinforced concrete floor, from which point it enters a hammermill. Large metal pieces are removed by hand before entering the hammermill. The output from the hammermill consists of slivers and small chunks of wood together with nails and other small pieces of metal. The material then moves from the hammermill to a screen operation by conveyor. Ferrous metal is removed enroute by magnetic separator and conveyed to a bin. The screening operation consists of two vibratory screens. Material failing to pass the first 4 inch screen is fed back to the hammermill for further processing. Material passing both the first and second screens feeds to a mulch bin for subsequent sale to nurseries. Material of the right size passing the first, but not the second screen is fed to bins for shipment to a pulp operation.

It is imperative that the material received be practically all wood and free of plastic, cement bags, etc. In return for bringing only clean wood waste, the hauler is charged no dumping fee.

A second operation in California utilizes a different system for separating, size reduction and screening. Dump trucks unload material either directly into a receiving pit or on a surge pile. A crawler-tractor crushes large scraps into manageable size and loads them into a 20' deep by 40' long receiving pit which is equipped with two bottom drag chains. From the drag chain the unprocessed wood moves up a 6' conveyor to a flotation vat where an agitator knocks off pieces of metal, gravel, dirt and other material from the floating wood. The damp clean wood moves from the flotation unit by another 6' conveyor to a wood hog which utilizes a punch-and-die cutting action to reduce the size of the wood. The

material is then transported on a 2' belt to two vibrating screens. On the way a magnet removes the ferrous metal scrap. Fines and sawdust are stored on the ground for aging prior to sale as mulch. Oversize pieces are sent back to the hog, and acceptable fibers are sent directly to waiting vans. This system can handle more non wood constituents than the first system, but in its present configuration could not handle the types of general demolition waste found in most of the 1001 loads at the 29 dumps visited in this study.

The risks associated with the supply and demand needs for reuse operation together with the capital needed for development of a system of high utility for processing general demolition and construction waste without presorting tends to inhibit development of this market. Government activity to reduce the risk or capital investment needed would act to spur subsequent private industrial entrance into this field.

METHODOLOGY & FIELD DATA

This study is characterized by the large amount of primary data that was gathered through field work, response cards, and interviews. In conjunction with this work a new technique for determining percent combustibles in mixed bulky waste was developed and evaluated.

The study results should be viewed in context with the methods used. Because of the heavy reliance on field-generated data, the collection and analysis of the data and methods employed will be discussed as follows:

- Essentials of the Methodology
- Training
- Statistical Methodology
- Stratifying the Sample
- Field Implementation
- Density Determination
- Volume Determination by Response Cards
- Wood Waste Generated by Construction Activity
- Estimating the Total Number of Buildings Demolished and Constructed Per Year in the United States
- Estimating the Energy Potential From Demolition and Construction Waste on National and Local Levels

Essentials of the Methodology

The primary purpose of the study was to determine the amount of demolition and construction waste generated in the United States annually and to determine what fractions of these total figures represent the combustible portion.

At the outset of the study it was intended that the following equation would be used separately for demolition waste and for construction waste to arrive at the number of tons of combustible debris generated annually from demolition and construction activities:

$$\underset{(1)}{\frac{\text{average } yd^3}{\text{building}}} \times \underset{(2)}{\frac{\text{tons}}{yd^3}} \times \underset{(3)}{\frac{\text{buildings demolished (constructed)}}{\text{year}}} \times \underset{(4)}{\%\ \text{combustible by weight}} = \frac{\text{tons of combustible}}{\text{year}}$$

(1) was determined from primary data obtained from members of the demolition and construction industries;

(2) was calculated from the weights of thirty sample truckloads of demolition waste and thirty sample truckloads of construction waste of known volumes;

(3) was determined by extrapolation from the figure on total number of residential buildings demolished in the United States, found in U. S. Bureau of the Census Report #C45, to obtain an annual figure on all categories of residential, commercial, and industrial buildings demolished.

Extrapolation was based on the ratio of residential buildings constructed or demolished to non-residential buildings (commercial and industrial) constructed or demolished. Data was derived from the annual building construction and demolition permit records of the ten cities visited. These calculations are based on the numbers of buildings demolished and constructed after obtaining a permit and do not cover unpermitted operations. Unpermitted operations occur most often in rural areas where levels of demolition activity are low and are expected to represent a negligible part of the total activity.

(4) was obtained from statistical analysis of the data collected at disposal sites in Philadelphia, Los Angeles, Minneapolis, Houston, St. Louis, Miami, Pittsburgh, Chicago, Atlanta and Detroit. A total of 29 disposal sites were visited and 1001 truck dumpings observed.

Early in the planning stage of the work it was agreed that "combustibles" would be construed as wood waste only.

Training

The data collection methodology for part (4) of the equation used visual estimation to measure percent combustibles by weight. Therefore, special training was instituted. The questions to be answered in the training phase were:

1. What were the best techniques for observing and estimating the volume of construction and demolition waste in a disposal operation?
2. What was the accuracy of the estimation?
3. Was the accuracy improved significantly by averaging the estimates of two or more observations?

A six week training session was initiated during which these issues were addressed. It was conducted at a suburban Philadelphia disposal site permitted by the State of Pennsylvania for demolition and construction waste. After meeting with site personnel, several areas were designated and cleared so that the training waste loads could be kept separate for future analysis. Arrangements were made with a local NAIDC demolition contractor to have his incoming 50 yd.^{3} trucks stop at a nearby scale to obtain gross and tare weight for the vehicle. Trash bins of 12-14 yd.^{3} and a dump truck were used in the separation of the wood fraction. The training area is diagrammed in Figure 8.

When a weighed truck pulled into the landfill area, the observers positioned themselves around the rear of the truck at safe distances and unobstructed observation points. The best location proved to be about 30° from the rear centerline of the truck. Observation of material was made while the load was dumped and after it was on the ground to make an estimate of the amount of wood and wood products in the load. Because this was a training exercise, estimates of the first loads were made on a volume basis until the observers developed a correlation between the volume and weight percentages.

Estimates of weight, date, time, source, truck weights, and general comments were recorded on a data sheet. All loads were photographed for subsequent analysis. Figures 9 through 11 show some of the loads.

Four JACA employees, went through the training program. Two held Bachelor's degrees and two were technicians with several years experience. It was not known how many loads would be required to develop an acceptable degree of accuracy (20%). Progress was monitored and terminated at 32 loads when accuracy was satisfactory.

Figure 1

LOCATION OF TRAINING AREA
DOMINO SALVAGE
PLYMOUTH MEETING, PA.

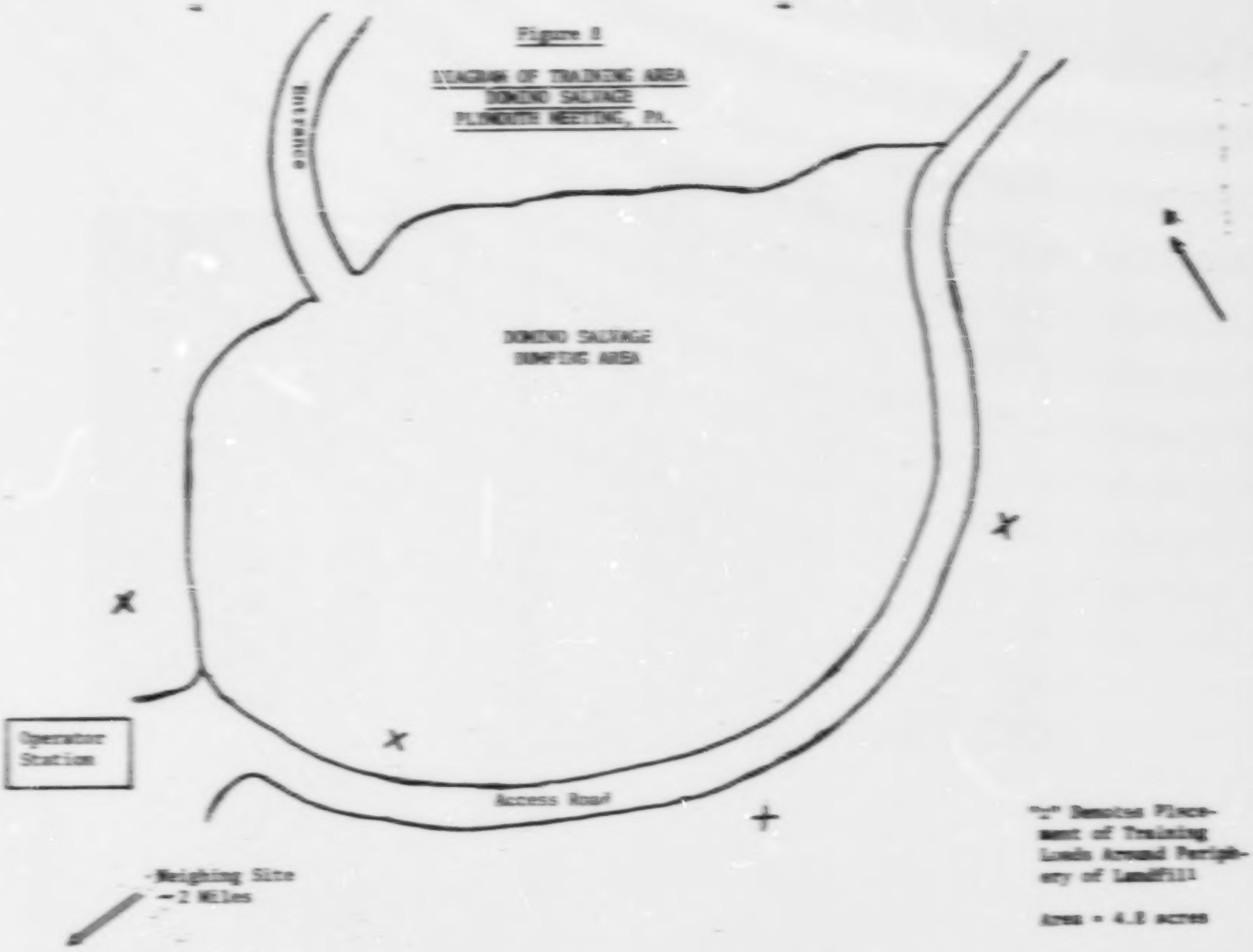


Figure 9

TYPICAL 40 YD.^{3} LOAD OF DEMOLITION WASTE AT LANDFILL

Figure 10

AN UNSEPARATED LOAD OF DEMOLITION WASTE WITH A HIGH PERCENTAGE OF WOOD

Figure 11

AMOUNT OF WOOD HAND-SEPARATED FROM DEMOLITION WASTE IN 1.5 HOURS DURING THE TRAINING PERIOD

The loads were hand separated into wood and non-wood piles. Portable trash dumpsters and a dump truck were used to transport the separated materials back to the scale. Because of the size and weight of some of the beams and concrete blocks, a front end loader was occasionally used as an aid in loading the receptable. Since the debris were often very small sized at the bottom of the pile, and these smaller pieces were often ground up when the front end loader raked the pile, the weight percentages of the remaining 10% or less were often estimated and added to the weigh ticket totals. The estimated remainder was less than two hundred pounds. All of the debris came from the Philadelphia area. Information as to the type of structure from which it originated was obtained from the drivers or dispatcher.

The actual percent combustible was obtained in the following manner:

$$\% \text{ Combustibles} = \frac{\text{gross weight of separated materials - wt. of container}}{\text{gross weight of incoming truck - wt. of truck}} \times 100$$

Thirty-two loads of demolition waste were hand separated and weighed during the training period. It was noted during the training period that demolition loads tend to occur most frequently with high percentage combustibles or low percentage combustibles rather than in the 30-70% range (Figure 12). This same condition prevailed in 100% observation in later field work (Figure 7).

A summary of the training results appears on Table 5. This summary shows an error of 5.49% when averaged over all 32 loads. This was within the pre-determined 20 percent tolerance established for the practical utility of the visual estimating technique. Table 5 also shows a reduction in error as the training continued. The error of the average of the first 10 loads was 4.99% and of the last 22 loads 1.75%. The average of trainees' absolute error per training truckload is shown in Figure 13.

Statistical Methodology

Predictive Versus Empirical Approaches

There are two techniques for estimating the quantity of demolition and construction waste and the percentage that is combustible. In the case of demolition waste, predictive techniques involve determining the composition of buildings presently being demolished on the basis of knowledge of materials and quantities, as well as the original construction techniques. Information concerning the age

Figure 12

FREQUENCY DISTRIBUTION
OF ACTUAL COMBUSTIBLE PERCENTAGE
-LOADS 1 to 32-

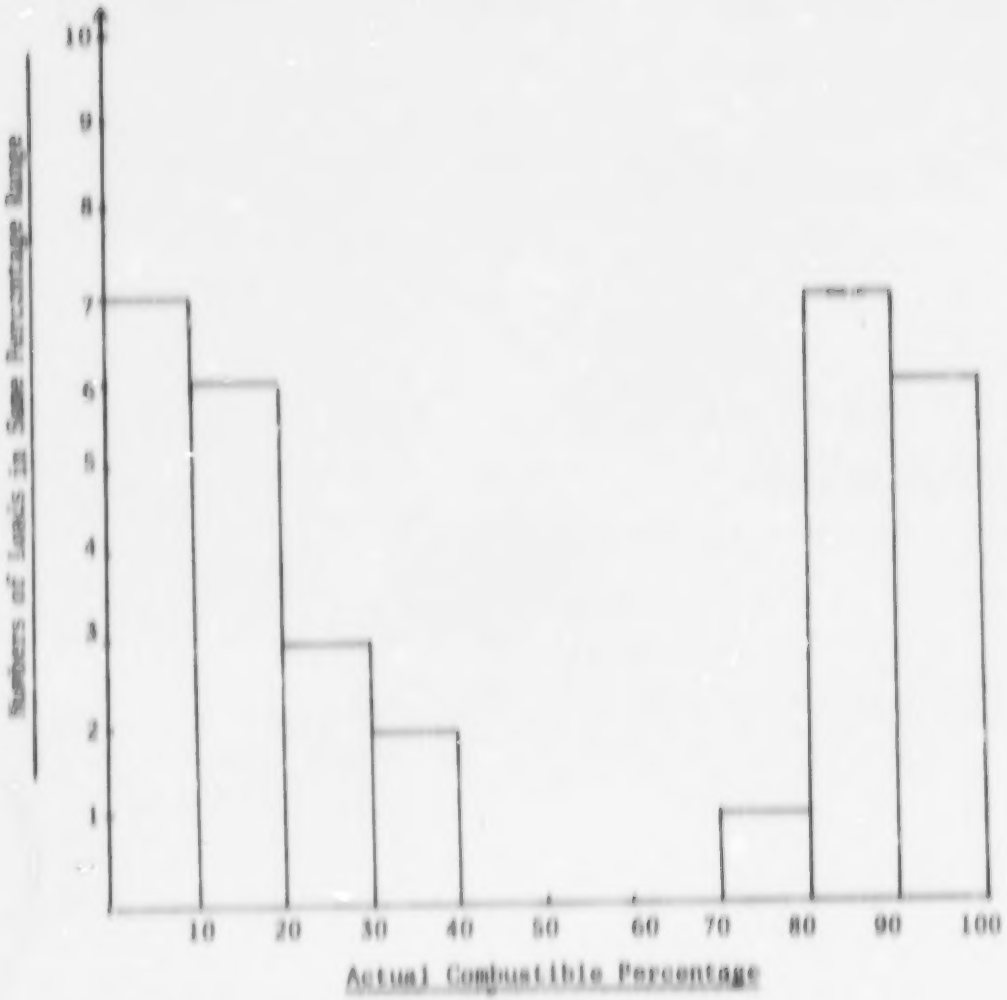


Table 5

SUMMARY OF TRAINING RESULTS

A. Total of 32 Loads

Actual % Combustible	46.09
Estimated % Combustible (ave.)	51.58
Error	5.49

1. Individual Estimates (all 32)	Observer #1	Observer #2	Observer #3	Observer #4
Estimated % Combustible	50.20	57.36	44.32	54.45
Error	4.11	11.27	-1.77	8.36

B. Last 22 Loads

Actual % Combustible	44.21
Estimated % Combustible (ave.)	45.96
Error	1.75

1. Individual Estimate (last 22)	#1	#2	#3	#4
Estimated % Combustible	57.2	53.2	40.8	54.4
Error	8.6	8.99	-3.37	10.19

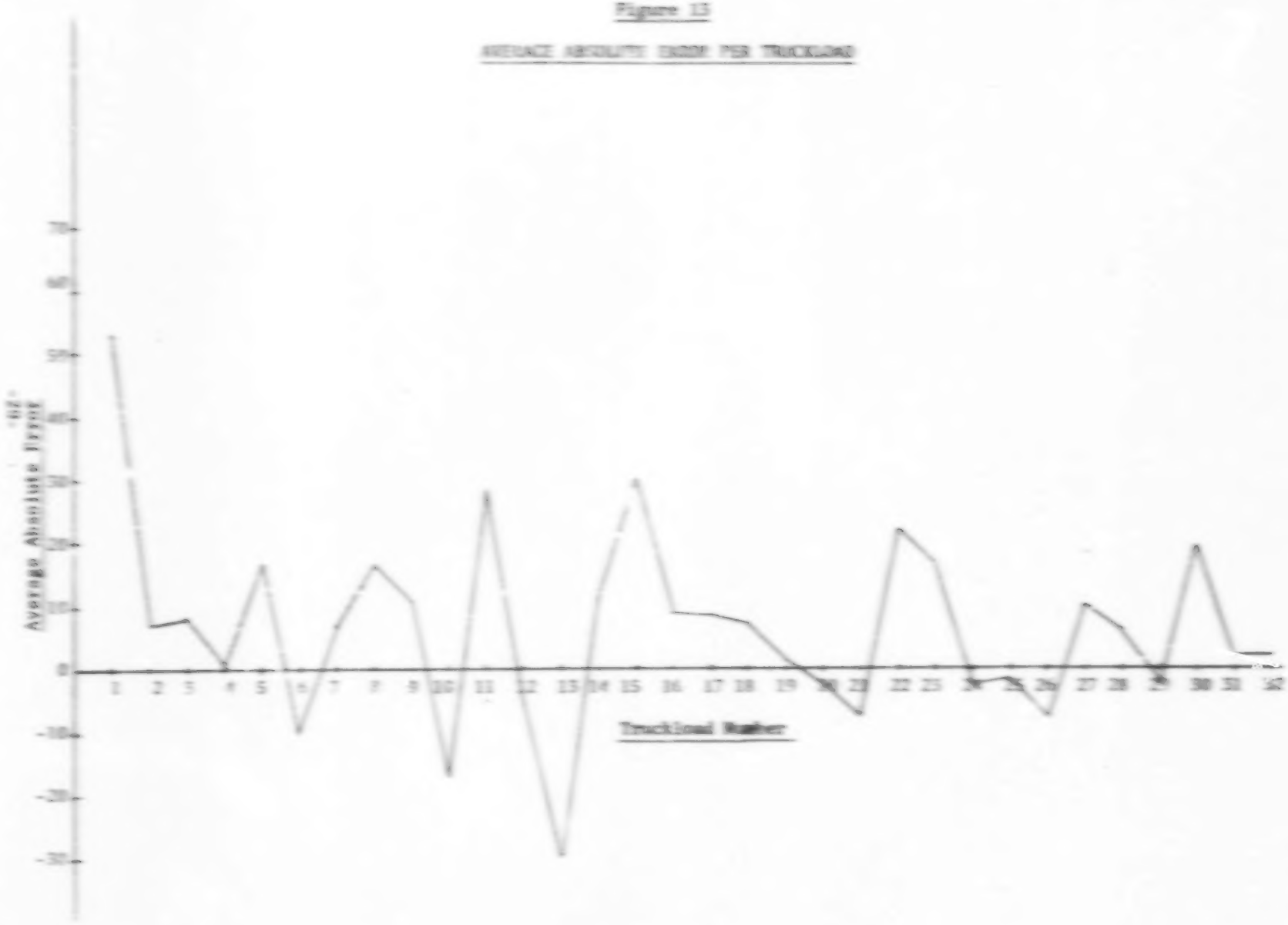
C. First 10 Loads

Actual % Combustible	50.21
Estimated % Combustible (ave.)	55.20
Error	4.99

1. Individual Estimates	#1	#2	#3	#4
Estimated % Combustible	46.17	66.5	51.67	----
Error	-4.04	16.29	1.46	----

Figure 15

AVERAGE ABSOLUTE ERROR PER TRUCKLOAD



of a structure being demolished, as well as the number of units of each type provides an estimate of the amount of demolition waste generated as well as the percentage that is combustible. This estimate is employed in conjunction with information that involves the use of predictive techniques covering the number of buildings demolished, the average number of cubic yards of waste generated per building and the density of the waste per cubic yard, to yield the total number of tons of combustibles available.

There are limitations that affect both techniques. Those affecting the predictive technique have been summarized in a report written by Wiesman and Wilson[7]. First, estimates of building composition at demolition will incorporate errors, since alterations, additions and replacements take place after the building is constructed. Second, the set of buildings being demolished is not a homogeneous combination of all types and sizes, and the use of the computed content of the "average" building may differ significantly from those being razed. Third, clean fill, or, waste not containing wood, metals, plastics, and etc., may be short circuited and never reach the dump site. Fourth, on many jobs, the demolition contractor leaves any basement or foundation one foot below grade intact, and fills the basement with non-wood waste from the structure. Any waste so diverted is not truly available, but is part of predictive estimates. Finally, original construction records kept by local governments often lack detail and inaccurate estimates may result.

Empirical sampling, combined with predictive techniques has some limitations. First, sampling involves the random selection of sites and times of observations and, it is often not possible to achieve this randomness because of time and budget constraints. To the extent that randomness is lacking, errors may enter into the estimation process. Second, the type of random sampling employed in this study involved a process of observation by trained technicians, and thus is subject to errors of measurement. Finally, since some predictive techniques are employed, these estimates may incorporate some of the inaccuracies mentioned above. The major sources of possible error involve the use of cubic yards of waste generated per demolition and the total number of buildings being demolished. To the extent that these averages are not representative, estimates will be off. Extreme caution was used by the contractor in the careful inclusion of randomness in the selection process and through training of the technicians in an attempt to minimize the first two problems. The third problem is reduced through gathering of background and on-site data and careful calculation of averages.

Errors in Sampling

The sampling process is subject to two types of errors. The measurement or non-sampling error occurs because of a difference between the actual value and the measured value. This kind of error arises from factors such as imperfect

observation, faulty questionnaires, inaccurate tallying, etc. The sampling error results from the chance selection of sampling units. This error occurs when a partial observation of the universe takes place. If the entire universe were studied, the sampling error would be zero.

The total error in a statistical survey such as this one is the sum of the measurement error and the sampling error. The major concern is to minimize the total error. Reduction of the measurement error is achieved by defining precisely the population to be studied and its traits, by refining the measurement process to the highest degree, and by training the individuals doing the measurement as thoroughly as practicable. These precautionary measures are usually costly, leading to the necessity of using small samples. However, small samples tend to have larger sampling errors. Therefore, there are two options available: the sample size can be kept small and the measurement made in a sophisticated manner, or the sample size can be large and the measurement made in an unsophisticated manner. The following example should help illustrate a method of estimating the percentage of combustibles in construction and demolition waste. Assume that a sophisticated measurement process would limit the sample size to 50 observations or an unsophisticated technique would employ trained observers to estimate the combustible proportion and would allow for a sample size of 300 observation's. Assume that the measurement error in the first case would be five percent and in the second case it would be ten percent. In estimating proportions, the formula for the maximum sampling error is given by:

$$(1)\quad \Delta = z\sqrt{\frac{\pi(1-\pi)}{n}}$$

Δ = sampling

z = normal curve deviate which is determined by the level of confidence

π = universe proportion being estimated

In the absence of information concerning the possible size of π, it is assigned a value of 1/2, which maximizes the expression $\pi(1-\pi)$, and therefore, maximizes Δ for a given level of confidence and sample size. In the cases cited above, if a level of confidence of 90% is employed:

$$(2)\quad \Delta_{90} = 1.645\sqrt{\frac{(.5)(1-.5)}{50}} = .116$$

$$\Delta_{90} = 1.645\sqrt{\frac{(.5)(1-.5)}{300}} = .047$$

Using a level of confidence of 90%, we observe:

$$(5)\quad \delta_{90} = 1.96\sqrt{\frac{(.5)(1-.5)}{50}} = .139$$

$$\delta_{90} = 1.96\sqrt{\frac{(.5)(1-.5)}{500}} = .056$$

Since:

Total Error = Sampling Error + Measurement Error, the following results are obtained, with 90% confidence:

Case 1 Total Error = .115 + .05 = .165

Case 2 Total Error = .047 + .10 = .147

with 95% confidence:

Case 1 Total Error = .139 + .05 = .189

Case 2 Total Error = .056 + .10 = .156

At both levels of confidence, the total error is smaller when the sample size is increased at the expense of a larger measurement error. In the case of this study, we chose the option of increasing the sample size as opposed to reducing the measurement error, and the cost of doing so was significantly less than reducing the measurement error.

Stratifying the Sample

In stratified random sampling, the universe is classified into mutually exclusive subgroups or "strata", and samples are drawn from each of these strata.

Sample statistics are calculated from each of these strata and are combined to yield an overall estimate of a population parameter. The basic purposes of stratified, as compared to simple random sampling, are to obtain a sample that closely resembles the universe from which it was drawn and to reduce sampling errors. These objectives are accomplished by grouping together into strata those elements which are more alike with respect to the characteristic under investigation than are elements in the universe as a whole. Stratification is most effective when the elements within strata are as homogeneous as possible, as regards the property to be studied, and the differences among strata are as great as possible.

In this study the demolition samples were to be stratified by type of structure. Initially, four strata were contemplated: residential, multi-unit residential, commercial and industrial buildings. Experience in the field led to a reduction in the number of strata to two: residential and other. This was due to the fact that many cities did not distinguish among the various types of structures or the required number of observations to define strata was not generated in each of the four areas. The same strata were initially proposed for the construction data. The number here was also reduced to two for the same reasons. The stratification by phase of construction was also considered but was abandoned after attempts to gather the data proved highly impractical within budget and time limitations.

Site Selection

Figure 14 indicates how the geographical site selection was accomplished. The United States was broken down into four areas, and a percentage of the total population calculated for each area. The ten cities were assigned to an area based on population percentages. This technique resulted in a selection of cities that would represent any regional peculiarities of building material and techniques.

Ten cities were selected on this area breakdown on the basis of construction and demolition activity. Within each of these ten cities disposal sites were chosen on the basis of activity at the site and the willingness of the operator to cooperate by allowing field technicians to make on site observations.

Stratification by Building Type

Once the cities had been selected, the desired number of observations in each stratum (residential and other) for construction and demolition were determined by averaging the number of construction and demolition permits issued in each city during the period 1970-1975. These permits were used to establish the ratio of residential to other units constructed or demolished. This ratio was then applied to the number 30, the desired number of observations

Figure 14

GEOGRAPHICAL DISTRIBUTION OF CITIES INCLUDED IN THE SURVEY

for each city, to determine the desired number of observations in each of the two strata for that city. The desired and observed stratification for demolition and construction are shown in Table 6.

Teams of two technicians each were sent to disposal sites in each of the ten cities. Each technician independently observed loads as they were dumped and the individual readings were averaged to obtain a better estimate (smaller variance) of the percent combustible. Varying lengths of time were spent in an effort to gather enough data to meet the desired stratification, which was universally met.

Since the observed samples exceeded the required or "desired" number at each location, a weighting technique was devised which allowed the use of all the data generated, even where the actual number observed exceeded the desired number. Weights were assigned in such a way as to keep the strata in the proper desired ratio.

The weighted technique calculated the percentage combustible for each city as the weighted mean of the two strata, employing the desired number of observations in each strata as weights. An example of this technique for Philadelphia is shown on Table 7.

To determine the overall percentage combustibles, the arithmetic mean and standard deviation of the ten weighted percent combustibles was calculated. Employing this datum a confidence interval for the overall percentage of combustibles was calculated as follows:

$$\bar{X}p - t_{.05}(s/n) \leq \overline{Mp} \leq \bar{X}p + t_{.05}(s/n) \qquad 95\%$$

where:

$\bar{X}p$ = mean of the ten weighted percent combustibles

s = standard deviation of the ten weighted percent combustibles

$t_{.05}$ = coefficient which is determined by the level of confidence

n = sample size (10)

Mp = mean percent combustible for the universe

Table 6

DEMOLITION AND CONSTRUCTION FIELD DATA STRATIFICATION

		Demolition		Construction	
		Residential	Non-residential	Residential	Non-residential
Philadelphia	Desired	25	5	25	5
	Observed	39	66	26	22
Los Angeles	Desired	24	6	23	7
	Observed	26	20	54	14
Chicago	Desired	22	8	26	4
	Observed	35	55	26	10
Detroit	Desired	25	5	35	5
	Observed	36	6	31	11
Miami	Desired	26	4	20	10
	Observed	56	12	22	10
Houston	Desired	24	6	26	4
	Observed	26	10	38	8
St. Louis	Desired	22	8	17	13
	Observed	23	25	21	13
Atlanta	Desired	26	4	19	11
	Observed	57	5	20	13
Pittsburgh	Desired	26	4	15	15
	Observed	57	11	15	15
Minneapolis	Desired	24	6	17	13
	Observed	35	18	20	13

Table 7

CALCULATION OF PERCENT COMBUSTIBLE DEMOLITION WASTE, PHILADELPHIA, PA

	Number of Observations		Percent Combustible
	Desired	Observed	
Residential	25	17	45.1
Non-residential	5	21	20.7

$$\text{Weighted percent combustible} = \frac{R_d \cdot P_r + N_d \cdot P_n}{R_d + N_d}$$

where:

R_d = number of residential observations desired

P_r = percent combustible observed from residential readings

N_d = number of non-residential observations desired

P_n = percent combustible observed from non-residential readings

$$\text{Weighted percent combustible} = \frac{25\ (45.1) + 5\ (20.7)}{25 + 5} = 41.04\%$$

For demolition $s = 13.12$

$$38.60 - 2.262\left(\frac{12+12}{5.16}\right) \leq \mu_p \leq 38.60 + 2.262\left(\frac{12+12}{5.16}\right)$$

$$29.92 \leq \mu_p \leq 47.28$$

For construction: $s = 8.54$

$$47.59 - 2.262\left(\frac{8.54}{5.16}\right) < \mu_p < 47.59 + 2.262\left(\frac{8.54}{5.16}\right)$$

$$41.62 \leq \mu_p \leq 53.56$$

The interpretation of the confidence interval is as follows: there is a ninety-five percent certainty that the mean percent combustibles of all demolition waste is between 29.92% and 47.28%. The calculation of the percent combustible of construction waste and the interpretation of the resulting confidence interval is analogous to that for demolition. Once the mean percent combustible was determined, the total number of tons of combustibles was calculated by employing this percentage in conjunction with data developed on the basis of predictive techniques. The calculation for demolition waste is:

$$TCD = A \cdot D \cdot B \cdot P$$

where

TCD = total number of tons of combustibles per year from demolition waste

A = average number of cubic yards of waste per building

D = average density of demolition waste

B = number of buildings demolished per year

P = percent combustible of demolition waste

The average number of cubic yards per building was determined from an NAHC cooperative questionnaire. The average density was determined in field experiments with JPCA technicians. The number of buildings demolished per year was determined from literature searches. The percent combustible was calculated above.

In the case of construction waste it was impossible to develop data from haulers as to the average volume of loads from typical waste sites, as was done via the questionnaire for demolition waste. These data were not available because of the long duration of construction activity.

The calculation for construction waste differs significantly from that for demolition waste.

$$TCC = P \cdot W$$

where:

TCC = total number of tons of combustibles per year from construction waste

P = percent of wood that is wasted in construction

W = total amount of wood consumed in building and construction.

The percent of wood that is wasted in construction was determined from information gathered through literature searches and discussions with building contractors based on their estimating procedures. The total amount of wood consumed is taken from existing government sources.

Collecting Field Data

The primary segment of this study utilized field measurements of properly stratified samples. The plan was to use a total of at least 600 random samples

from three sites at each of ten cities visited. In the final analysis, 100% samples were obtained. This sample size was large enough to fully account for geographical differences in building sites and to provide for different sizes and types of buildings. Trained observers were used to estimate the percent combustibles as the trucks dumped their loads. A satisfactory measurement accuracy by this means would be 20% for all sample totals. The training showed that much better than 20% accuracy was obtained. The objective in each city studied was to collect enough samples (percent combustible values) for demolition and construction waste to meet the previously determined requirements in each category of a sixty sample, stratified set.

The first data collection was done in the Philadelphia area. The Annual Building Construction Reports for the years 1970-1975 were obtained to determine the stratification, in preparation for actual fieldwork. Construction and demolition permits for the past 5 months were examined to determine the recent activity levels in each stratum. The contractors whose names appeared frequently on these permits were contacted to determine which Philadelphia area landfill sites they were using and arrangements were made with landfill operators to station field observers at five local sites.

The activity in demolition and construction was extremely low during the initial data collection phase as compared to the activity levels during the earlier training session. This indicated that the generation of demolition and construction waste was sporadic. As a result, the fieldwork was rescheduled to coincide with periods of high demolition and construction activity in order to get the most samples during field visitations.

It was evident that a refinement in the scheduling of cities was extremely important. Following discussions with the National Association of Demolition Contractors of our objectives, Mr. Ron Dokell, President, offered the Association's assistance and, together with the Energy and Recycling Committee provided assistance pertaining to our visits to the ten cities. The NADC committee supplied names of local members who aided in scheduling of fieldwork to coincide with high demolition activity. These contacts were also helpful in directing us to the landfills where most of the waste was being hauled.

Arrangements were made to visit three landfills at each of the ten cities. Because one of the determining factors as to where demolition and construction will be dumped is the cost of hauling based on distance, the observation of three local sites helped neutralize intracity peculiarities in activity or composition of waste.

The method of obtaining percent combustible data followed the procedure described in the training section. At safe observation points, each load of construction and demolition debris was analyzed while being dumped and while on the ground to estimate the percent combustible by weight. The driver of the vehicle was questioned briefly as to what building category provided the waste.

Depending on activity levels in each city, observers spent one to two weeks on site, and in some instances had to return to a city to satisfy the stratification requirements. The stratification for the city was referred to periodically during the week to determine whether sufficient residential, commercial, and industrial loads were being sampled. Photographs were taken at several dumping sites for future reference.

Construction activity evidenced at the ten cities was mainly in the form of small truckloads and portable bins of wastes generated in renovation, roofing, and siding projects. Very little waste was observed from new building construction. One explanation for this phenomenon is that waste generated on construction projects is disposed of on site rather than paying dumping fees at a landfill. Therefore, it was necessary to schedule return visits to obtain fully stratified, 60 sample sets of construction samples.

Some of the city building reports did not distinguish between commercial and industrial demolitions. Therefore, these two categories were combined into "non-residential" construction and demolition for all the cities surveyed. Decreasing the number of strata did alleviate some of the problems in obtaining a proper sample. After the data on the 10 cities was reviewed, it was necessary to return to Miami, St. Louis, and Chicago for sufficient data on construction. Sufficient demolition data was collected in all ten cities on the first visit because the demolition volume to building volume ratio is so large that continuous landfill dumping is necessary.

Individual observers' estimates were averaged at each of the ten cities, and it was found that the difference between one observer's average for the entire sample and the average of two observers for the entire sample was negligible. Therefore, one observer was sent to each of the four cities where insufficient construction waste data had been collected on the first visit.

The field data results collected on percent combustibles in the ten cities weighted in accordance with the method shown in Table 7 are tabulated in Table 8.

Density Determination

The density of the loads was a second piece of primary data to be obtained in the field. During the initial training session, thirty-two loads of demolition waste were weighed and separated at a local landfill site. The demolition trucks were 50 cubic yard size capacity.

In order to use the equation presented in the section entitled National and Area Estimates, a value for the average density of demolition waste was needed. The concentration of the various components of demolition waste such as wood, brick, concrete, dirt, and the permitted road weight of a particular truckload help determine the density of the load and the volume to which the truck can be

Table 8

WEIGHTED PERCENT OF WOOD IN DEMOLITION AND CONSTRUCTION WASTE

FIELD DATA

City	% Wood Demolition	% Wood Construction
Philadelphia	41	42
Los Angeles	63	48
Chicago	44	60
Detroit	42	45
Houston	27	63
St. Louis	51	60
Miami	37	45
Pittsburgh	27	36
Atlanta	20	40
Minneapolis	34	51
Average Weighted % Combustible	39	48

filled. Often a 50 $yd.^3$ capacity demolition truck with high density components may be filled to only 30 $yd.^3$ whereas a truck with a high percentage of wood is generally filled to volume capacity. The average volume of thirty-two 50 yd^3 truckloads averaged 40 $yd.^3$.

$$P_{load} = \frac{\text{weight of load}}{1080\ ft.^3}$$

When the average densities for the 32 loads were calculated using the above equation, the value for the density of demolition waste was found to be 25 $lbs/ft.^3$. This figure was considered accurate for this study because the percentage combustible values for the 32 training loads had good distributive representation from both low percentage and high percentage combustible loads.

Volume Determination by Response Cards

In order to use the equation presented in the National and Area Estimates section a value for the average number of cubic yards of waste generated per type of building demolished or constructed was needed.

$$\frac{\text{Avg. } yd.^3}{\text{Bldg. (const./demo.)}} \times \frac{\text{tons}}{yd.^3} \times \frac{\text{bldgs. (const./demo.)}}{\text{year}} \times \frac{\% \text{ combust. by weight}}{} = \frac{\text{tons of combust.}}{\text{year}}$$

To determine the volume of waste generated in the demolition of buildings, the NAIC cooperated with JACA Corp. in administering a response card program, which supplied data collected by seventeen volunteer members of NAIC. Information on the response card is shown by the following sample.

Respondent No. 20

1) Job Started 8/9 2) Job Finished 8/12

Check Type of Building		Enter No. of Truckloads	Enter Truck Size
3) Residential ____	4) units = 2	5) 24	6) 40 cu.yds.
7) Commercial ____			
8) Industrial ____			

Respondents remained anonymous through a respondent numbering system, and the geographical distribution was statistically sound. One card was completed per demolition jol. The information entered on the card included duration of job, type of building, number of units if residential, number of loads, and the truck size. The sample card above indicates 960 cubic yards of demolition waste were generated from the duplex structure in 4 days.

The NAHC response card program ran for approximately three months, yielding 200 responses from the seventeen respondents. Following completion, cards were separated according to building category, and the average volume of waste per demolished building was calculated for residential, commercial, and industrial buildings.

AVERAGE VOLUME OF WASTE PER BUILDING

Residential	450 yd^3/bldg.
Commercial	2022 yd^3/bldg.
Industrial	3860 yd^3/bldg.
Overall	1370 yd^3/bldg.

From other information included on the response cards, the average duration of a demolition job could also be determined.

AVERAGE DURATION OF DEMOLITION JOB

Residential	5.87 days
Commercial	9.56 days
Industrial	14.7 days
Overall	6.92 days

The distribution of response cards by respondent and the cities represented by the response program are shown in Figure 15 and Table 9 respectively.

Figure 19

NUMBER OF RESPONSE CARDS COMPLETED BY RESPONDENTS

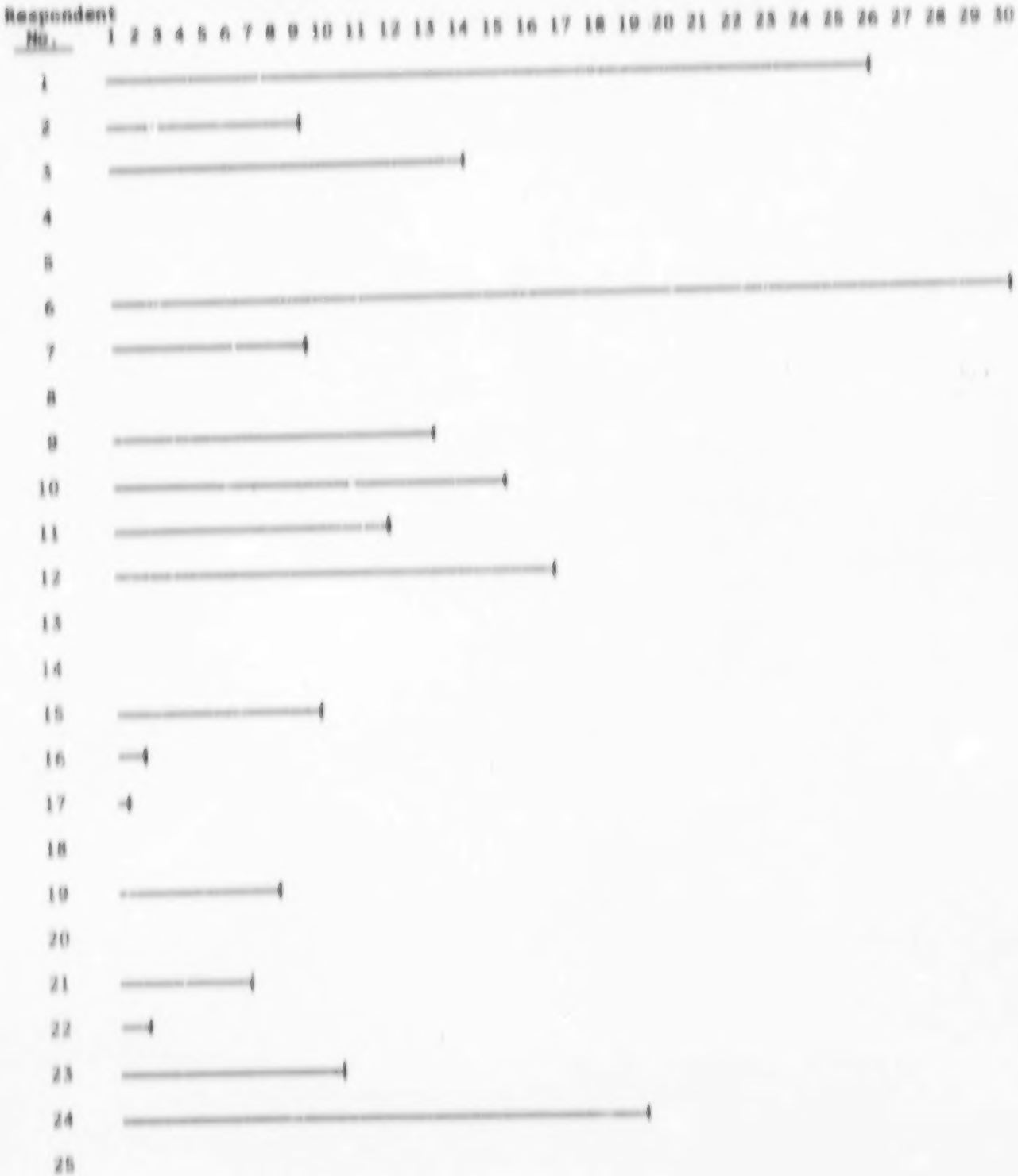


Table 9

CITIES REPRESENTED IN VOLUNTEER RESPONSE CARD PROGRAM

Skippack, Pa. (Philadelphia)

McKeesport, Pennsylvania

Windsor, Connecticut

Atlanta, Georgia

Akron, Ohio

Columbus, Ohio

Fort Wayne, Indiana

Chicago, Illinois

Lyons, Illinois

Riverside, Illinois

South Suburban, Illinois

Maywood, Illinois

Elmhurst, Illinois

Skokie, Illinois

Detroit, Michigan

St. Paul, Minnesota

Houston, Texas

Tucson, Arizona

Seattle, Washington

Wood Waste Generated by Construction Activity

As previously discussed, lengthy job duration, variation in methods of disposal of construction waste, and the inability of members of the hauling industry to provide average estimates of volume of waste generated per each construction job frustrated attempts to determine the volume of wood waste generated in the construction of a residential building, a commercial building, and an industrial building. Therefore, it became necessary to develop data on the basis of estimates made by construction contractors on the percentage of wood waste generated on their jobs. Contractors were requested to estimate the wood waste as a percentage of wood ordered per construction job. The results of this survey of 20 contractors indicated that an average of 7.4% of wood delivered is wasted in the process of construction. This average was tested for significance by the following equation:

$$\bar{x}_w - t_{.025}\left(\frac{s}{\sqrt{n}}\right) \leq \mu_w \leq \bar{x}_w + t_{.05}\left(\frac{s}{\sqrt{n}}\right)$$

At a 95% level of confidence, $5.28 \leq \mu_w \leq 9.52$

Estimating the Total Number of Buildings Demolished Per Year And Constructed Per Year in the United States

Annually, the U. S. Department of Commerce, Bureau of the Census issues a report entitled Housing Units Authorized for Demolition in Permit-Issuing Places. The report gives the total number of permits issued for housing unit demolition annually in the 327 U. S. Cities having a population of 50,000 or more. The report also gives a United States total figure based on reports from permit issuing places authorizing the demolition of 1 or more housing units.

Using the figures presented for the number of housing units demolished in cities over 50,000 population (.34 of total U. S. Population 1970 Census) as well as the individual cities populations, a statistical evaluation was conducted to determine whether a linear relation existed between population and number of units demolished using methods of linear regression analysis. The equation $y = -3.09 + .0018\ x$ was derived where y = number of units demolished and x = the size of population. This equation explained 61% of the variation for this relation. Therefore, there would be a certain degree of error in pursuing the calculation of a U. S. total for demolition of housing units by this method.

While the above equation might be useful in predicting the amount of demolition for an area, given its future population estimate a more reliable estimate was needed. Therefore, it was decided that the figures for U. S. total number of housing units demolished based on reports from permit issuing places authorizing the demolition of 1 or more housing units would be used. The Bureau of the Census states that these annual figures are based on reports from areas which represent about 80-85% of the population and would therefore imply that these figures probably represent 95% of the total U. S. housing unit demolition rate.

To convert from units demolished per year to residential buildings demolished per year, the average number of units per building demolished from the building reports of the ten cities visited was calculated. This was found to be 1.4 units per building.

1975	1974	1973	1972	1971	1970
121,972	139,450	149,141	141,915	137,426	122,773

121,972 units/yr ÷ 1.4 units/building = 87,123 buildings/yr.

To determine the total residential and non-residential buildings demolished per year, the ratio of residential to non-residential buildings,demolished per year in the ten cities surveyed,was computed and averaged from their respective building construction and demolition reports. The following equation was used:

$$\frac{\text{no. of residential buildings demolished}}{\text{year}} \times \frac{1}{.803} = \frac{\text{no. of residential and non-residential buildings demolished}}{\text{year}}$$

$$87{,}123 \times \frac{1}{.803} = 108{,}497$$

To determine the total number of buildings constructed per year in the United States a similar approach was used. Using data on residential construction obtained from the National Association of Homebuilders which showed housing units constructed per year (Table 7) the following procedure was used.

$$\frac{\text{residential units constructed}}{\text{year}} \div \frac{\text{avg. units}}{\text{bldg. constructed}} = \frac{\text{residential bldgs. constructed}}{\text{year}}$$

$$\frac{1,512,900}{1} \div 2.5 = 605,160$$

$$\frac{\text{residential buildings constructed}}{\text{year}} \times \frac{1}{.724} = \frac{\text{residential and non-residential buildings constructed}}{\text{year}}$$

$$605,160 \times \frac{1}{.724} = 835,856$$

Estimating the Energy Potential from Demolition and Construction Waste on National and Local Levels

The heating value of wood was taken as 8613 BTUs per pound. By multiplying the tons of combustibles generated annually from these two sources, the energy potential of the waste wood can be calculated on a national level:

Demolition

$$\frac{\text{avg. yd}^3}{\text{bldg.}} \times \frac{\text{tons}}{\text{yd}^3} \times \frac{\text{bldgs. demo.}}{\text{year}} \times \text{\% combustible} \times \frac{\text{BTU's}}{\text{ton}} = \frac{\text{Total BTU's}}{\text{year}}$$

$$1369.8 \times .337 \times 108,500 \times .386 \times (1.72 \times 10^7) = \frac{3.3 \times 10^{14} \text{ BTUs}}{\text{year}}$$

Construction

$$\text{tons of wood consumed annually by construction industry} \times \text{average \% wasted per job in construction} \times \frac{\text{BTU's}}{\text{ton}} = \frac{\text{total BTU's}}{\text{year}}$$

$$55,000,000 \times .074 \times (1.72 \times 10^7) = \frac{4.5 \times 10^{13} \text{ BTU's}}{\text{year}}$$

Total energy potential from demolition and construction nationwide = $\frac{3.75 \times 10^{14} \text{ BTU's}}{\text{year}}$

To determine the energy potential from demolition waste for a given local area (i.e. the ten cities included in this study) the above equation is used with a substitution of number of buildings demolished per year within the city for the number of buildings demolished on the national level. The local weighted percent combustible figure (Table 8) can be substituted for the national average of 59%. The volume per building must be recalculated in accordance with the average ratio of residential, commercial, and industrial buildings indicated in the building reports and the appropriate volumes shown per building.

To calculate the energy potential available from construction waste on a local level, the amount of wood consumed must be estimated. The method used was to set up an equality which relates amount of wood consumed by the construction industry on a given level to the number of buildings constructed on that level.

$$\frac{\text{Wood consumption nationwide by construction industry}}{\text{buildings constructed nationwide}} = \frac{\text{Wood consumption by city by construction industry}}{\text{buildings constructed by city}}$$

e.g. Chicago

$$\frac{35{,}000{,}000 \text{ tons}}{835{,}806 \text{ bldgs.}} = \frac{x}{7482}$$

x = wood consumption by Chicago construction industry = 104,000 tons per year

Using the construction waste energy potential equation:

$$104{,}000 \times .074 \times (1.72 \times 10^{7}) = \frac{1.3 \times 10^{11} \text{ BTU}}{\text{year}}$$

The energy potentials from both construction and demolition debris calculated by these methods for each of the ten cities are shown in Table 10.

Table 10

ANNUAL BTU POTENTIAL OF WOOD WASTE FROM DEMOLITION AND CONSTRUCTION WASTE FOR TEN CITIES

City	Tons of Combustibles From Demolition and Construction per Year	BTU's per Year From Construction and Demolition
Philadelphia	1.9×10^5	3.5×10^{12}
Los Angeles	6.7×10^5	$.11 \times 10^{12}$
Chicago	4.0×10^5	6.9×10^{12}
Houston	1.1×10^5	1.9×10^{12}
Detroit	4.9×10^5	8.5×10^{12}
Miami	$.67 \times 10^5$	1.1×10^{12}
St. Louis	2.3×10^5	4.0×10^{12}
Atlanta	$.42 \times 10^5$	$.72 \times 10^{12}$
Pittsburgh	1.0×10^5	1.8×10^{12}
Minneapolis	$.67 \times 10^5$	1.2×10^{12}

DISCUSSION OF ACCURACY OF RESULTS

This section will discuss errors incorporated in the estimations of combustibles. Because of the different estimating methods used, for demolition and for construction wastes, error will be analysed separately.

Demolition Waste

$$\frac{\text{avg. yd}^3}{\text{building}} \times \frac{\text{tons}}{\text{yd}^3} \times \frac{\text{buildings demolished}}{\text{year}} \times \frac{\%\ \text{combustible}}{\text{by weight}} = \frac{\text{tons combustible}}{\text{year}}$$

(1) (2) (3) (4)

The above equation previously presented was used to develop a figure for the total number of tons of combustible demolition waste generated annually. For ease of explanation, numbers are used to label each step.

In the calculation of Step 1, the waste volume data from the NAHC response card program was averaged by building category and the overall weighted average was then computed. Computations were made for standard error on the mean for each category as follows:

Residential Waste Volumes

Classes	f
0-499	66
500-999	27
1000-1499	2
1500-1999	8
2000-2499	2
2500-2999	0
3000-3499	1
3500-3999	0
4000-4499	1
	107

The standard deviation of the sample = 658.02

The standard error ($S_{\bar{x}}$) = $\frac{S}{\sqrt{n}}$ = 63.5

Commercial Waste Volumes

Classes	f
0-1999	51
2000-3999	11
4000-5999	5
6000-7999	4
8000-9999	0
10000-11999	2
12000-13999	0
14000-15999	0
16000-17999	1
	72

The standard deviation of the sample = 2756.55

The standard error $(S_{\bar{x}}) = \frac{S}{\sqrt{n}} = 324.5$

Industrial Waste Volumes

Classes	f
0-2999	13
3000-5999	5
6000-8999	1
9000-11999	1
12000-14999	0
15000-17999	0
18000-20999	0
21000-23999	0
24000-26999	0
27000-29999	0
30,000	1
	21

The standard deviation of sample = 2414.24

The standard error $(S_{\bar{x}}) = \frac{S}{\sqrt{n}} = 290.87$

	Standard Error Per Category	Weighting Factor	Weighted Standard Error Squared
Residential	65.5	.18	129.82
Commercial	524.5	.52	28458.10
Industrial	290.87	.30	7614.48
		1.00	36182.25

Overall $S_{\bar{x}}$ = $\sqrt{36182.4}$ = 190.22

Percent Error = $\frac{190.22}{1370}$ = 13.9% = total error involved in the calculation of Step 1.

In the calculation of Step 2, the weights of 30 loads of demolition debris, each with a volume of 40 cubic yards, were used to determine an average density value.

Classes	f
12000-14999	5
15000-17999	2
18000-20999	6
21000-23999	5
24000-26999	1
27000-29999	4
30000-32999	4
33999-35999	0
36000-38999	1
39000-41999	1
42000-44999	0
45000-47999	1
48000-50999	1
	31

The standard deviation of the sample = 9477.64
The standard error ($S_{\bar{x}}$) = $\frac{S}{\sqrt{n}}$ = 1692.84

Error per ft^3 = $\frac{1692.44}{1080}$ = 1.57

Percent Error = $\frac{1.57}{25}$ = 6.3%

Step 3 of the equation shows the number of buildings demolished per year. Data from the Bureau of the Census Report C45, were used here which gave the estimated total number of permitted building demolition from 85% of the population. The error on this part of the equation was assumed minimal since the remaining 15% of the population was probably from rural areas in which little demolition activity occurs.

Step 4 of the equation is the percentage combustibles by weight data which was collected during the fieldwork in ten cities. Results of the training period showed the error to be about 5.5%.

Calculation of total error for demolition (TE) $= (E_1^2 + E_2^2 + E_3^2 + E_4^2)^{\frac{1}{2}}$

$= (13.9^2 + 6.3^2 + 0 + 5.5^2)^{\frac{1}{2}}$

$=(193.21 + 39.69 + 0 + 30.25)^{\frac{1}{2}}$

$= 16.22\%$

and if Step 3 involves a maximum error of about 5% then,

$TE = (13.9^2 + 6.3^2 + 5.0^2 + 5.5^2)^{\frac{1}{2}}$

$= (193.2 + 39.69 + 25.0 + 30.25)^{\frac{1}{2}}$

$= 16.97\%$

Construction Waste

% of wood waste in construction $\times$ tons of wood consumed annually by construction $=$ Tons of wood wasted by construction

The above equation was used to calculate the amount of wood wasted in building construction annually in the U. S. The calculation of the figure for percentage of wood wasted in construction is the only part of the equation that involves some error as the estimates of twenty construction contractors were used.

Estimated Construction Wood Waste per Construction Job

10
4
10
1
12.5
10
10
0
5
10
10
5
1
2
10
5
15
10
15
5

Total 148.5
Average ($\bar{x}$) = 7.4 per construction job

The standard deviation of the sample = 4.64
The standard error ($S_{\bar{x}}$) = $\frac{S}{\sqrt{n}} = \frac{4.64}{\sqrt{20}}$

The error (E) = $\frac{S_{\bar{x}}}{\bar{x}} = \frac{1.0}{7.4} = 13.5\%$

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